



pp & pA: Results and Expectations

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For the PHENIX Collaboration



Synergies of pp and pA Collisions with an Electron-Ion Collider

RIKEN BNL Research Center Workshop
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pp&pA: Cold QCD studies in PHENIX

Cold nuclear effects

Necessary for sQGP studies

(n)FF, (n)PDF

Including saturation (CGC)

Factorization, Universality, Evolution

Factorization breaking, modified Universality

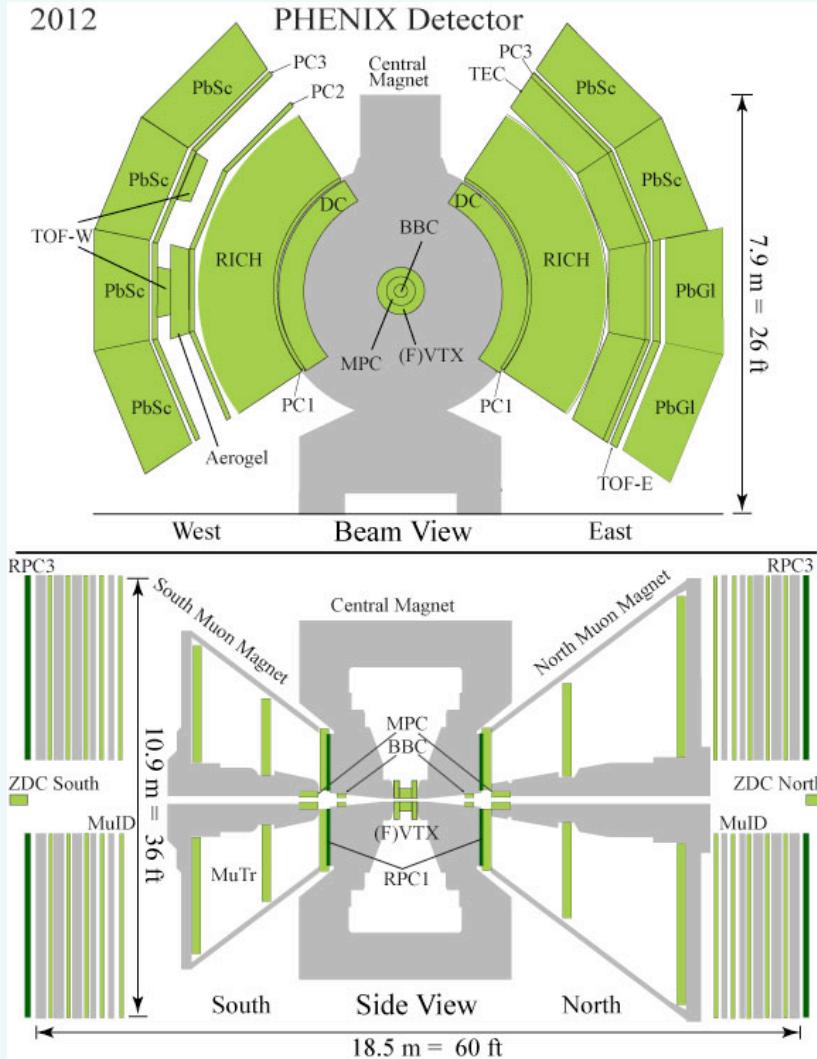


- Cross sections
- Spin asymmetries
- Correlations

Data up to 2016 (the last PHENIX data taking Run)

See Nils Fege talk about sPHENIX plans (2020+)

PHENIX Setup



π^0, γ, η

Electromagnetic Calorimeter: $|\eta| < 0.35$
Muon Piston Calorimeter: $3.1 < |\eta| < 3.9$

$\pi^\pm, e, J/\psi \rightarrow e^+e^-$, $W \rightarrow e$: $|\eta| < 0.35$

Drift, Pad Chambers, VTX ($|\eta| < 1$)
Ring Imaging Cherenkov Counter, ToF
Electromagnetic Calorimeter

$\mu, h^\pm, J/\psi \rightarrow \mu^+\mu^-$, $W \rightarrow \mu$: $1.2 < |\eta| < 2.4$

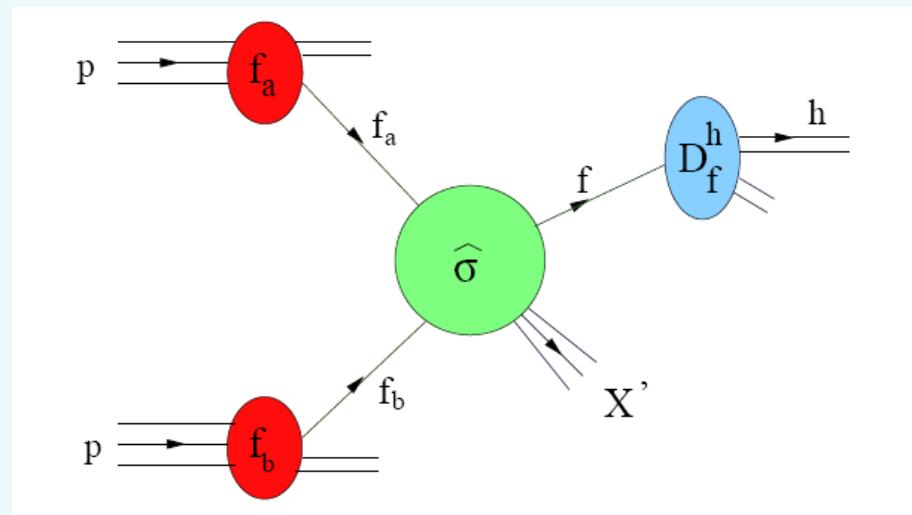
Muon Id/Muon Tracker
FVTX

Event vertex&time, (rel) luminosity,
local polarimetry, etc.

BBC: $3.0 < |\eta| < 3.9$

ZDC: $|\eta| > 6.5$

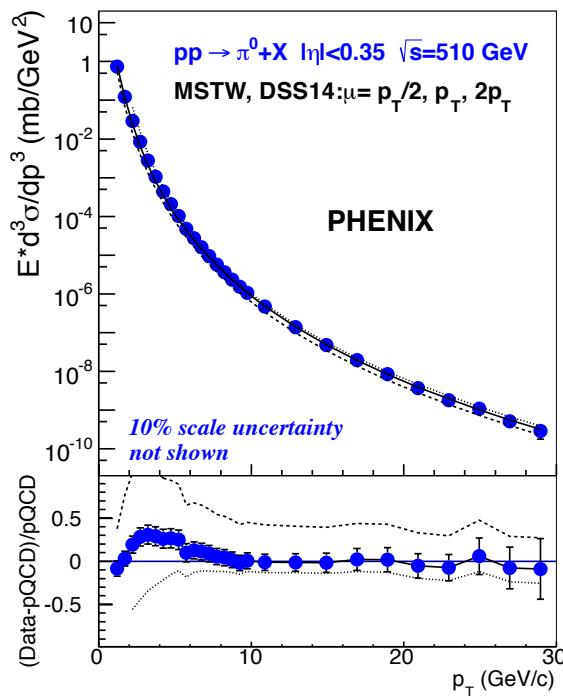
Cross section etc.



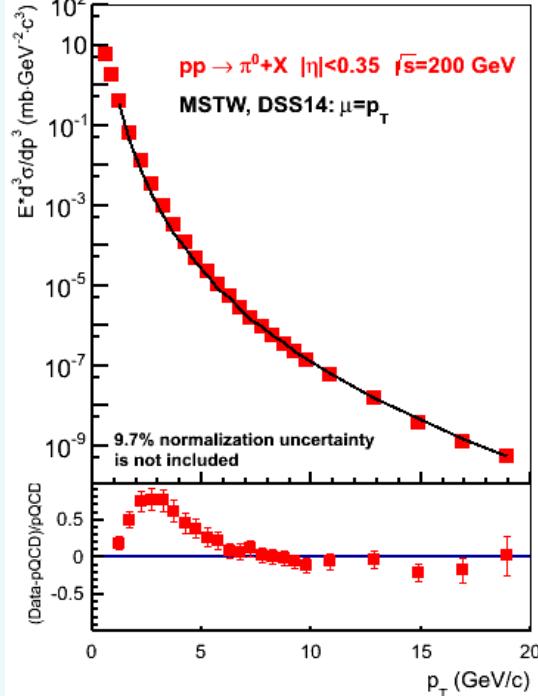
pp: Cross section, \sqrt{s} dependence

Mid-rapidity $p+p \rightarrow \pi^0 + X$

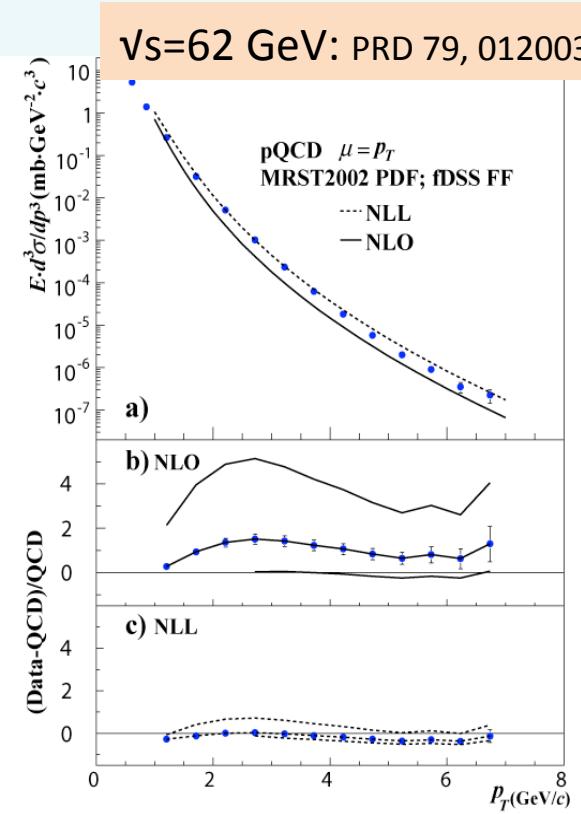
$\sqrt{s}=510$ GeV: PRD93, 011501 (2016)



$\sqrt{s}=200$ GeV: PRD 86, 072008



$\sqrt{s}=62$ GeV: PRD 79, 012003

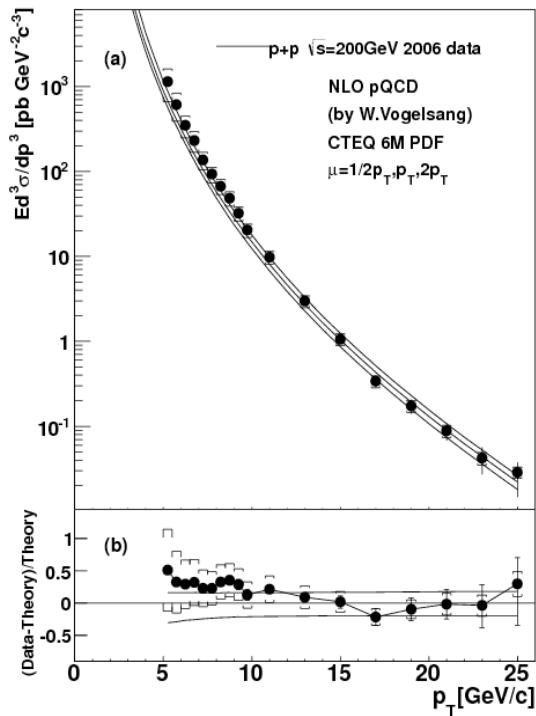


NLO pQCD in excellent agreement with data at $p_T > 5$ GeV/c

NLO pQCD not enough, soft gluon resummation needed

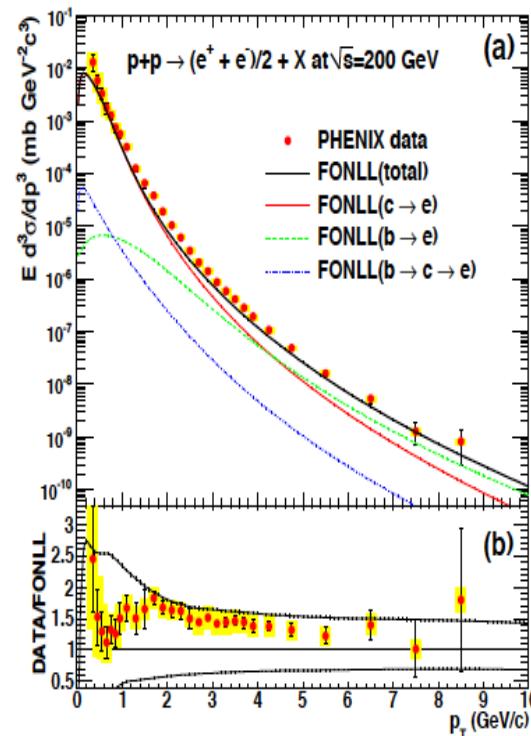
pp: Cross sections

$pp \rightarrow \gamma X$
PRD 86, 072008 (2012)



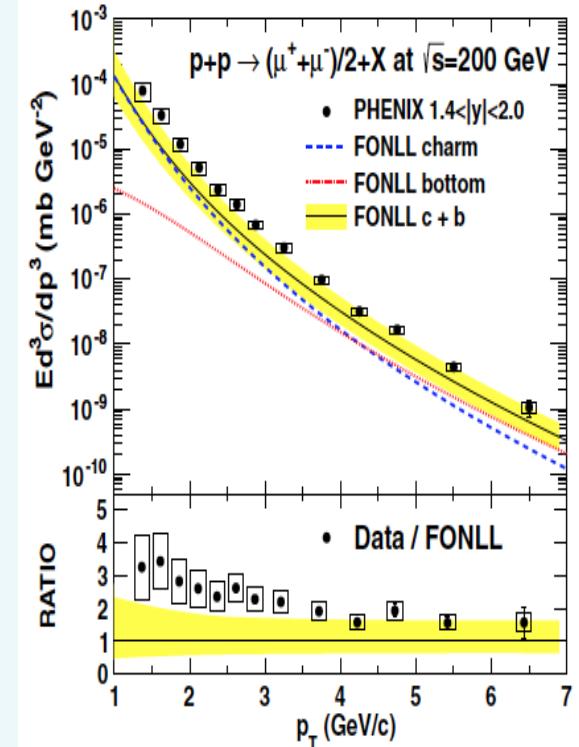
NLO pQCD in excellent agreement with data

$pp \rightarrow eX$
PRC 84, 044905 (2011)



FONLL in good agreement with data

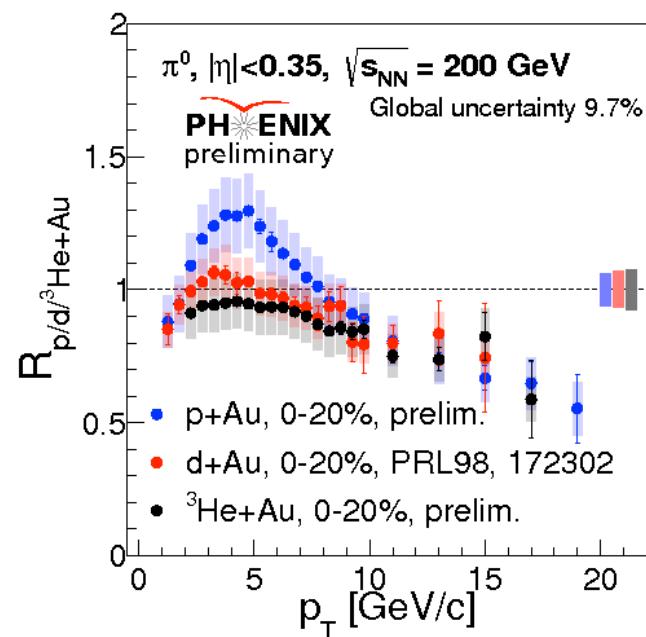
$pp \rightarrow \mu X$
PRD95, 112001 (2017)



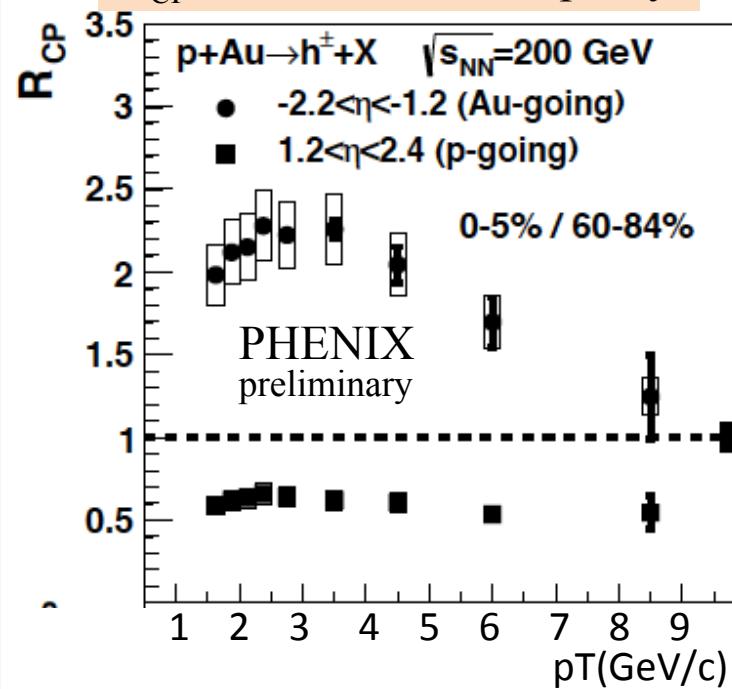
FONLL in reasonable agreement with data

pA: π^0 , h^\pm

R_{pA} : π^0 in central rapidity



R_{CP} : h^\pm in forw/back rapidity



High p_T : $R < 1$

Moderate p_T : $R_{pAu} > R_{dAu} > R_{{}^3\text{He}Au}$

Proton size fluctuations, energy loss in CNM, mult. scattering, shadowing etc.

No models can yet reproduce a peak at ~ 5 GeV/c

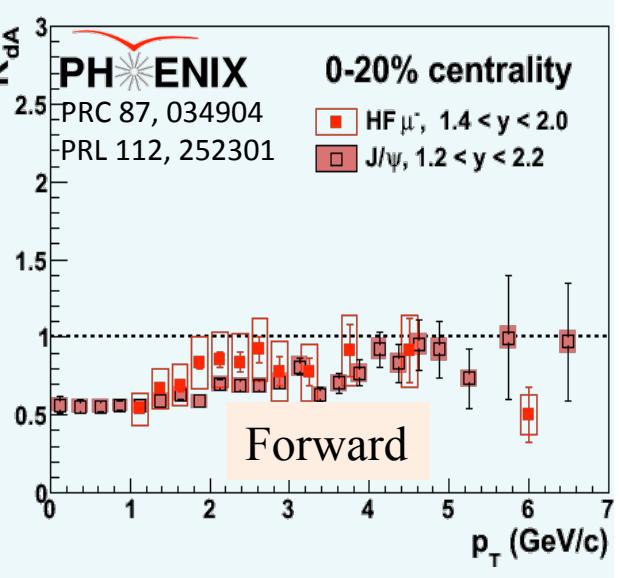
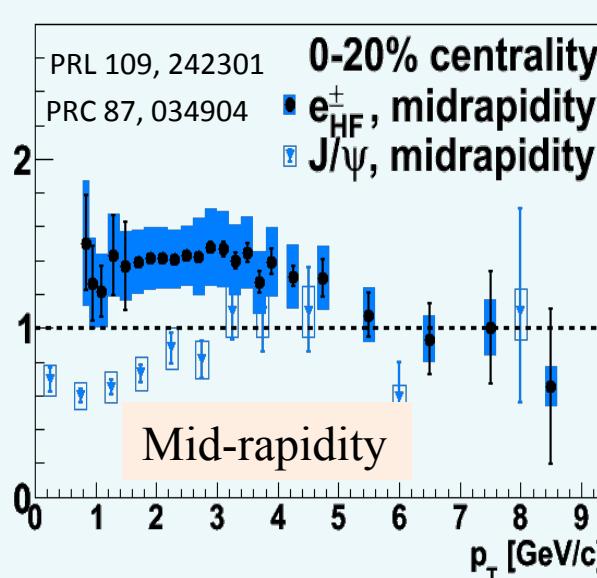
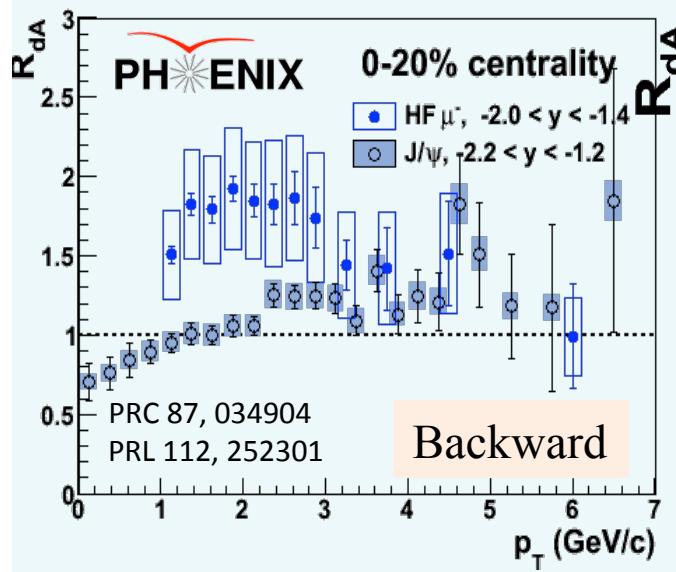
p-going: $R_{CP} < 1$

Shadowing? Saturation?

Au-going: $R_{CP} > 1$

Anti-shadowing?

p(d)A: Heavy Flavor



HF is suppressed in d-going direction and enhanced Au-going direction

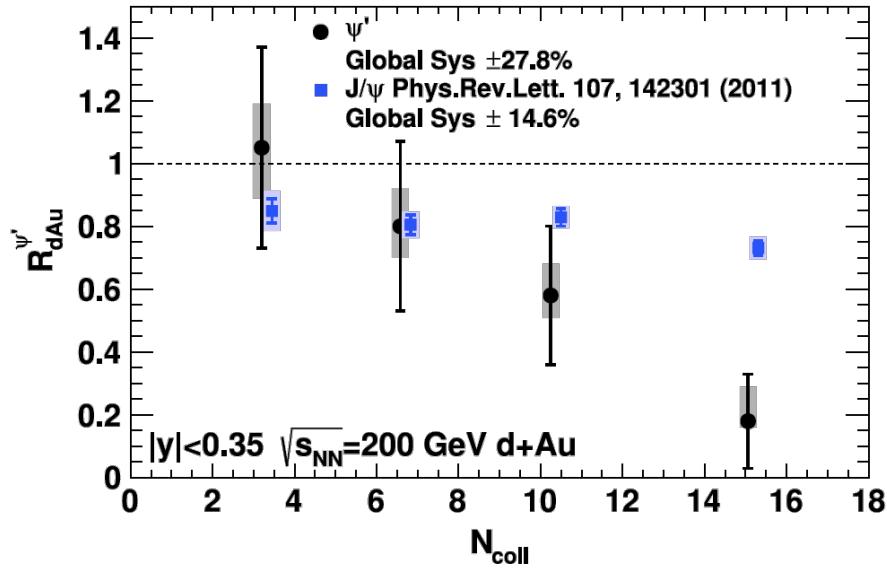
Similar to light hadrons

Parton scattering, shadowing, energy loss, etc.

J/ ψ breakup

p(d)A: Charmonia

PRL 111, 202301



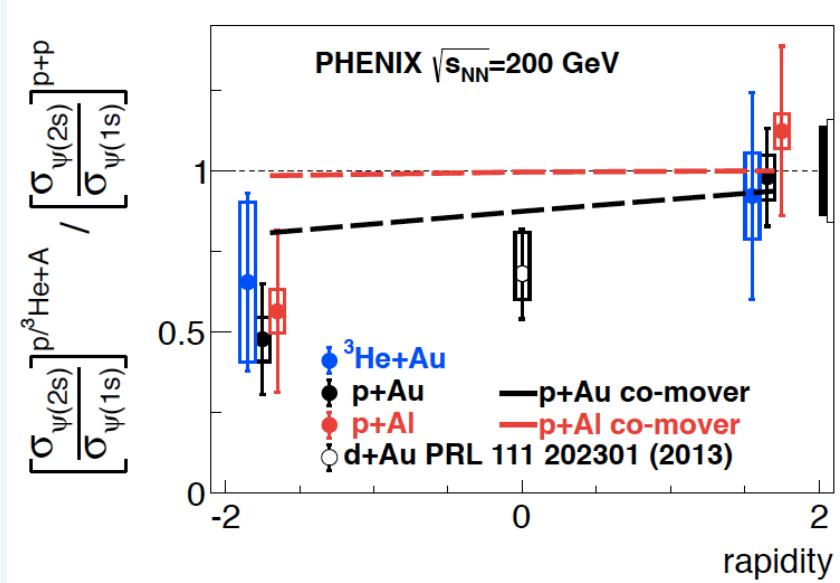
Larger suppression of ψ' at nucleus going direction

Breakup due to interaction with co-moving particles

More data coming: Incl. J/ψ , Upsilon, single leptons

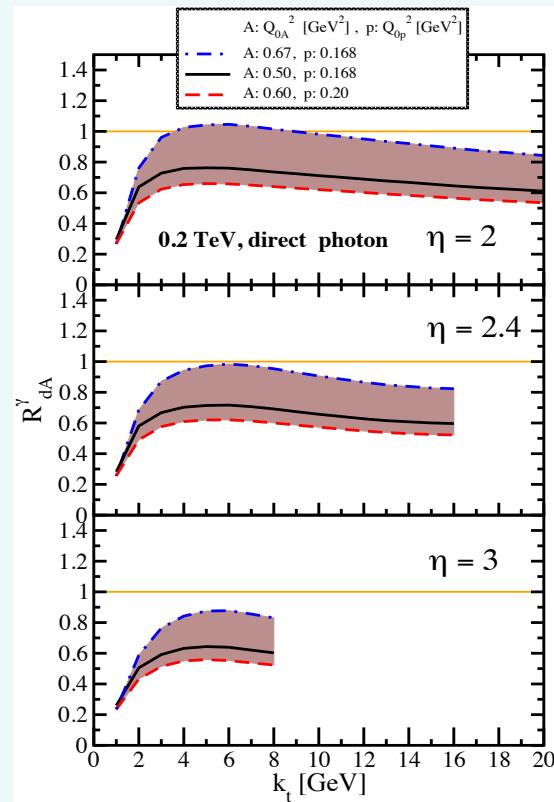
Breakup of quarkonia due to interaction with nuclear matter
Larger suppression of the weakly bound state ψ'

PRC 95, 034904 (2017)

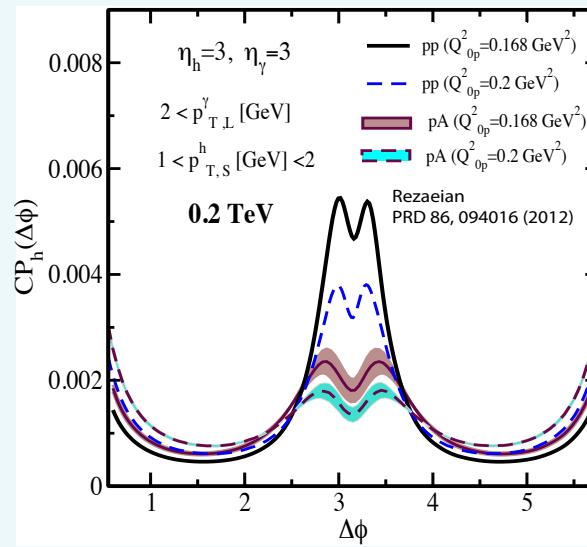


$p(d)A$: direct photons

CGC prediction for direct photon R_{pA}



γ -h forward-forward correlations



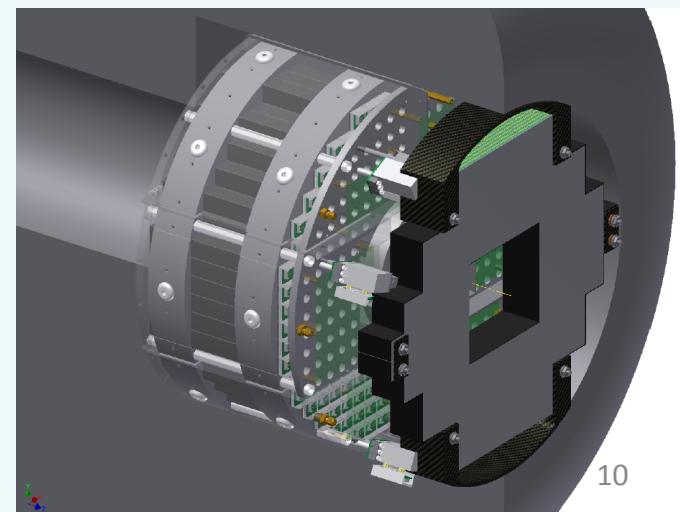
Selects large-x quark in p(d) and low-x gluon in A

MPC-EX: EMCAL + Preshower

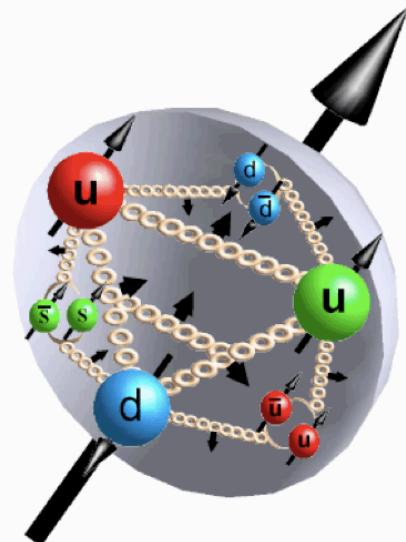
$3.1 < |\eta| < 3.8$

π^0/γ separation to > 80 GeV/c

Analysis of 2016 dAu data is ongoing

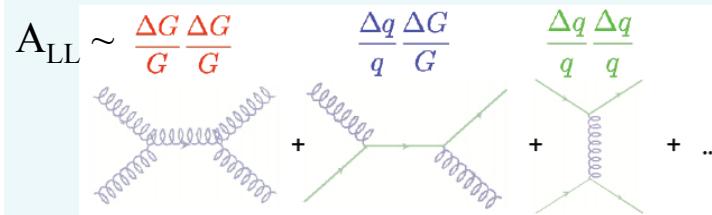
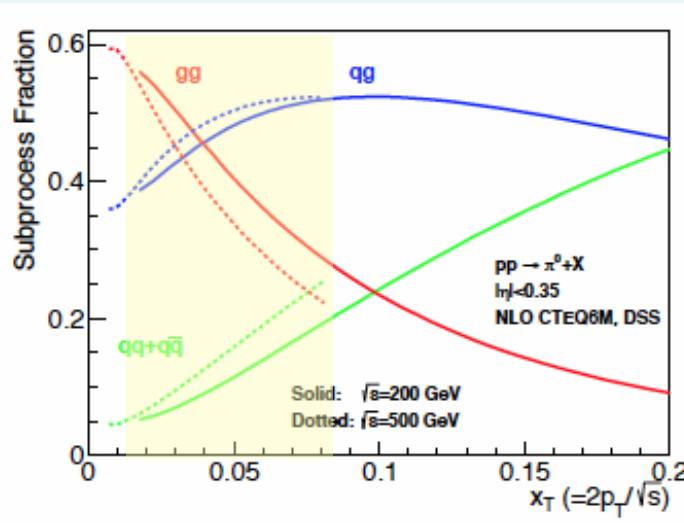


Spin Asymmetries



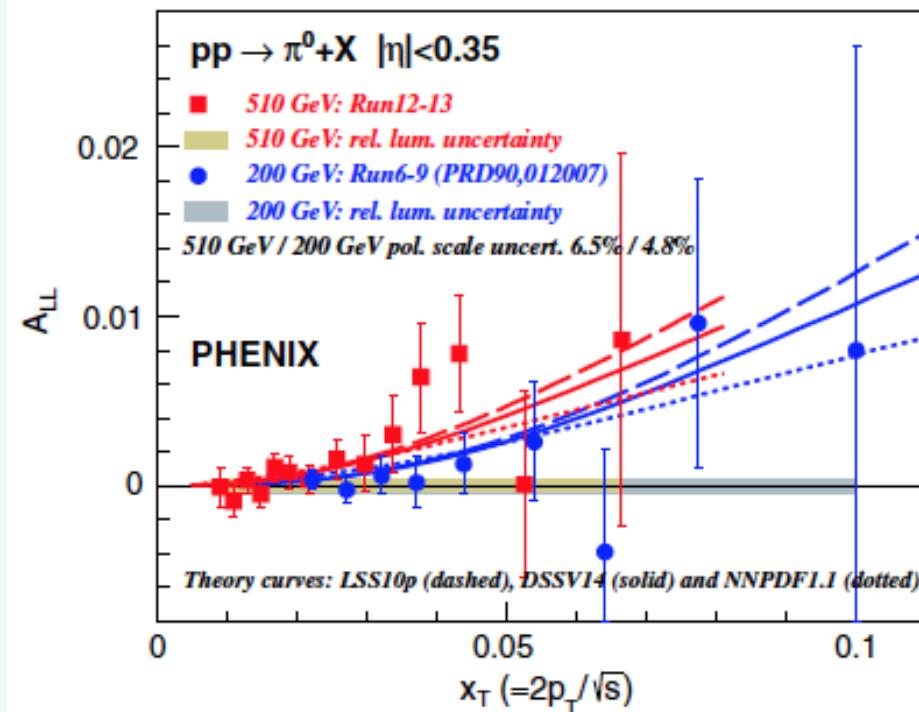
$\Delta G: \pi^0 A_{LL}$

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_z$$



The most abundant probe in PHENIX
(triggering + identification capability)

PRD93, 011501 (2016)



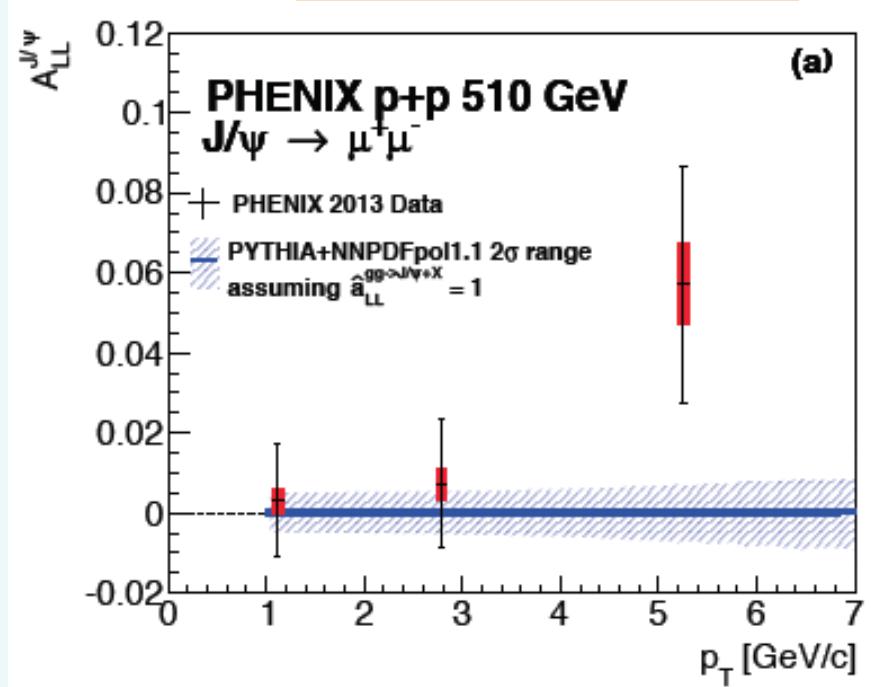
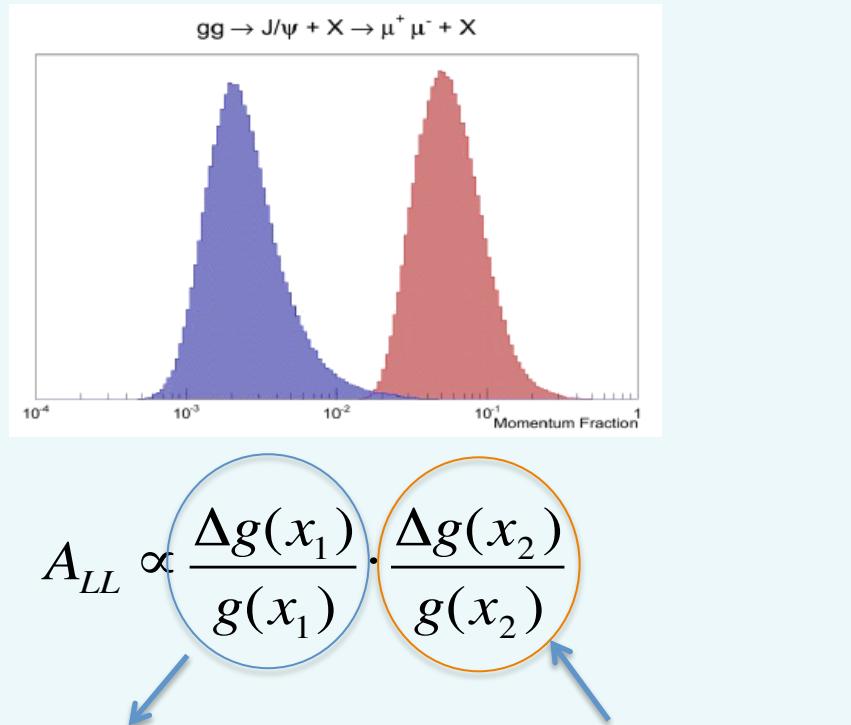
Non-zero A_{LL} associated with non-zero ΔG !

ΔG : Towards lower x

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_z$$

$pp \rightarrow J/\psi$ at $\sqrt{s}=510$ GeV $1.2 < |\eta| < 2.4$

PRD 94, 112008 (2016)



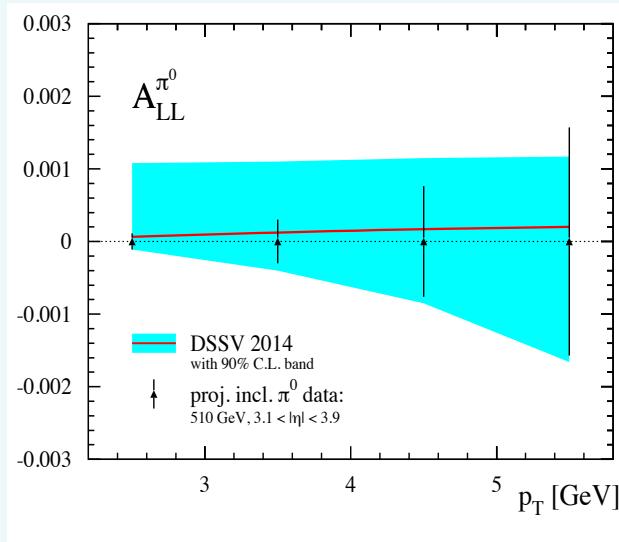
J/ψ production mechanism uncertainty
Not yet in the global fit

ΔG : Towards lower x

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_z$$

Projection

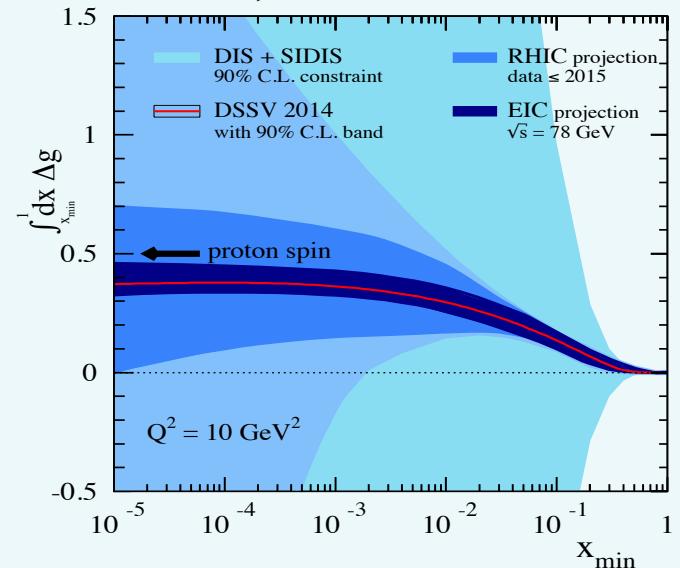
π^0 : $3.1 < |\eta| < 3.9$



From available
PHENIX+STAR
data from 2011-15



Aschenauer, Stratmann, Sassot
PRD 92, 094030



π^0 in forward region at $\sqrt{s}=510$ GeV:

Based on collected 2013 data
Probes lower x down to $\sim 10^{-3}$

Other channels also being measured
(but with weaker stat. power)

$\gamma, \eta, \pi^\pm, h^\pm$, heavy flavor through
e and μ , $h-h$, $\gamma-h$

$$d_L \bar{u}_R \rightarrow W^-$$

$$u_L \bar{d}_R \rightarrow W^+$$

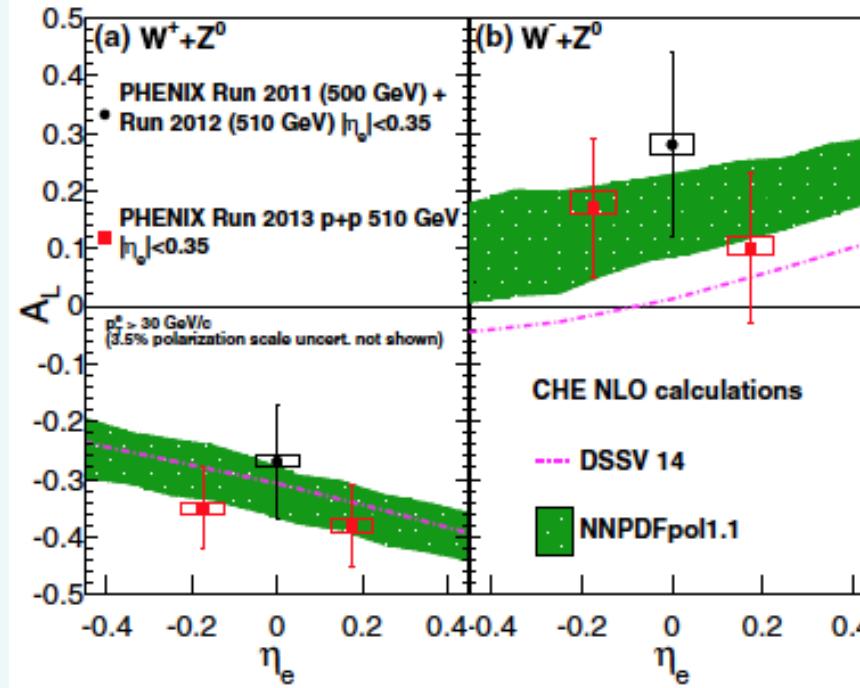
$\Delta q\text{-bar}$: $W^\pm \rightarrow e^\pm$

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_z$$

$$|\eta| < 0.35$$

Constrains flavor separated (anti-)quark polarization at high $Q \sim M_W$ at $x > 0.05$, with no fragmentation involved (as in SIDIS)

PRD93, 051103 (2016)



$$d_L \bar{u}_R \rightarrow W^-$$

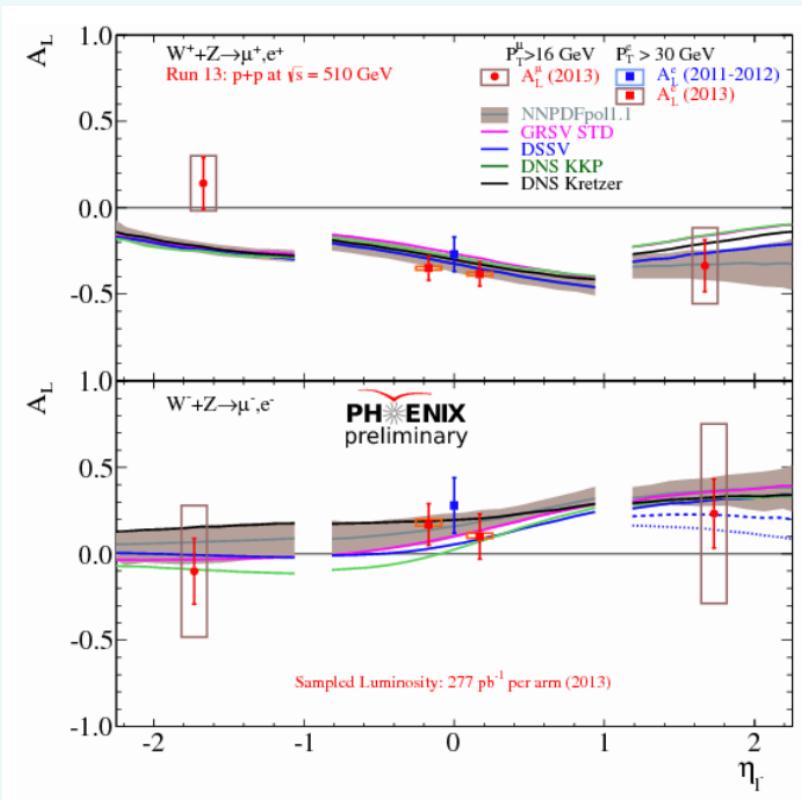
$$u_L \bar{d}_R \rightarrow W^+$$

$$\Delta q\text{-bar: } W^\pm \rightarrow \mu^\pm$$

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_z$$

$$1.2 < |\eta| < 2.4$$

Constrains flavor separated (anti-)quark polarization at high $Q \sim M_W$ at $x > 0.05$, with no fragmentation involved (as in SIDIS)



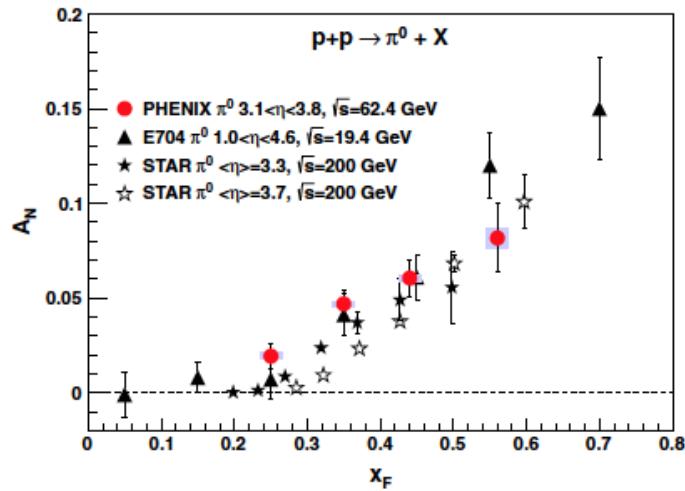
Uncertainties are large due to sizable background ($S/B = 0.2-1$)

Working to reduce syst. uncertainties

Publication in preparation

Forward-rapidity π^0 A_N

PRD90, 012006 (2014)



Collinear (higher twist) pQCD predicts

$$A_N \sim 1/p_T ?$$

No fall off is observed out to $p_T \sim 5$ GeV/c

STAR showed no fall off up to ~ 7 GeV/c

Naïve collinear pQCD predicts

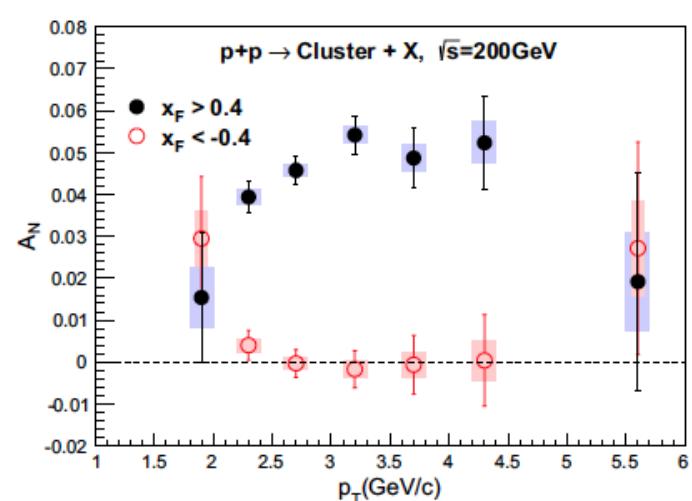
$$A_N \sim \alpha_s m_q / p_T \sim 0$$

Asymmetries survive at highest \sqrt{s}

Non-perturbative regime!

Asymmetries of the ~same size at all \sqrt{s}

Asymmetries scale with x_F



Underlying mechanism?

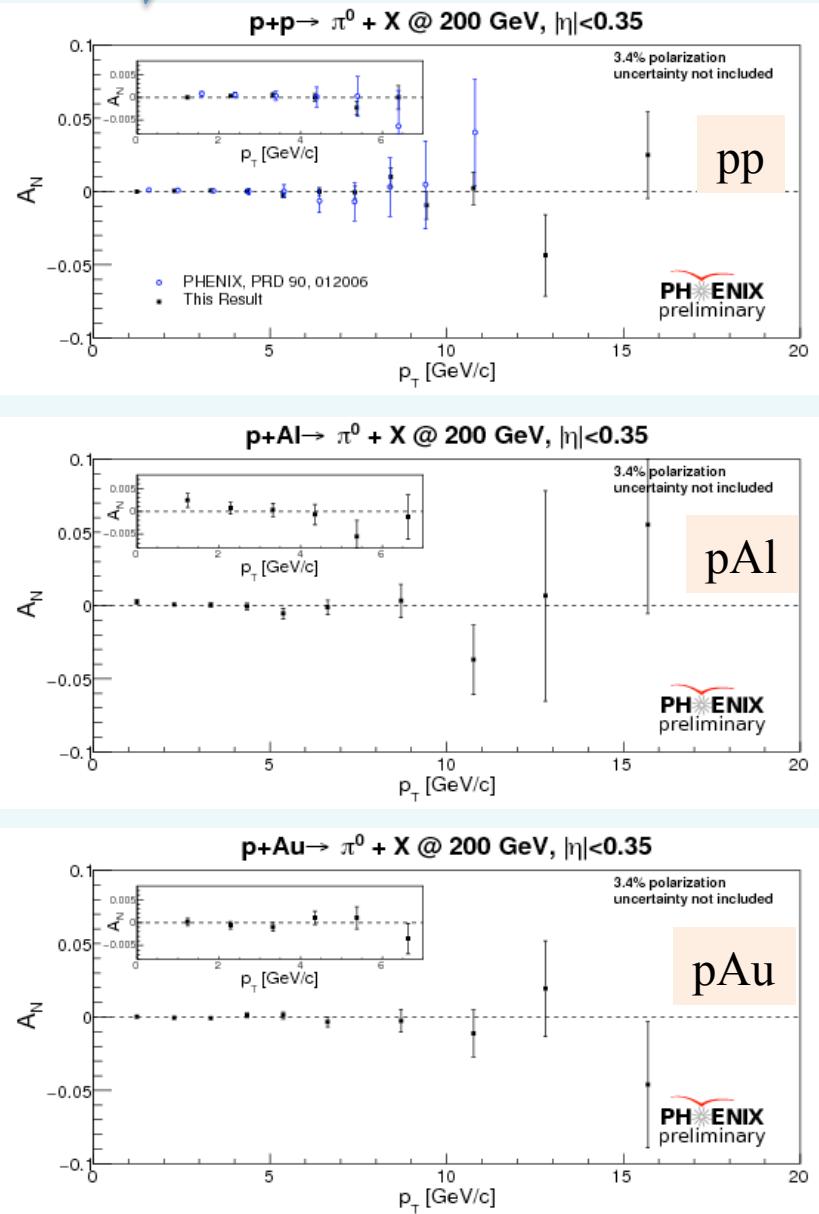
May involve initial state effect (Sivers-like), final state effect (Collins-like) or others



- Imaging in momentum space
- Transversity



Mid-rapidity π^0 A_N



Improved pp results from 2015!

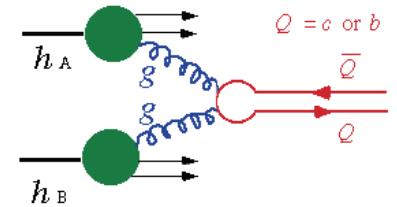
Consistent with 0

To 3×10^{-4} precision level at low p_T

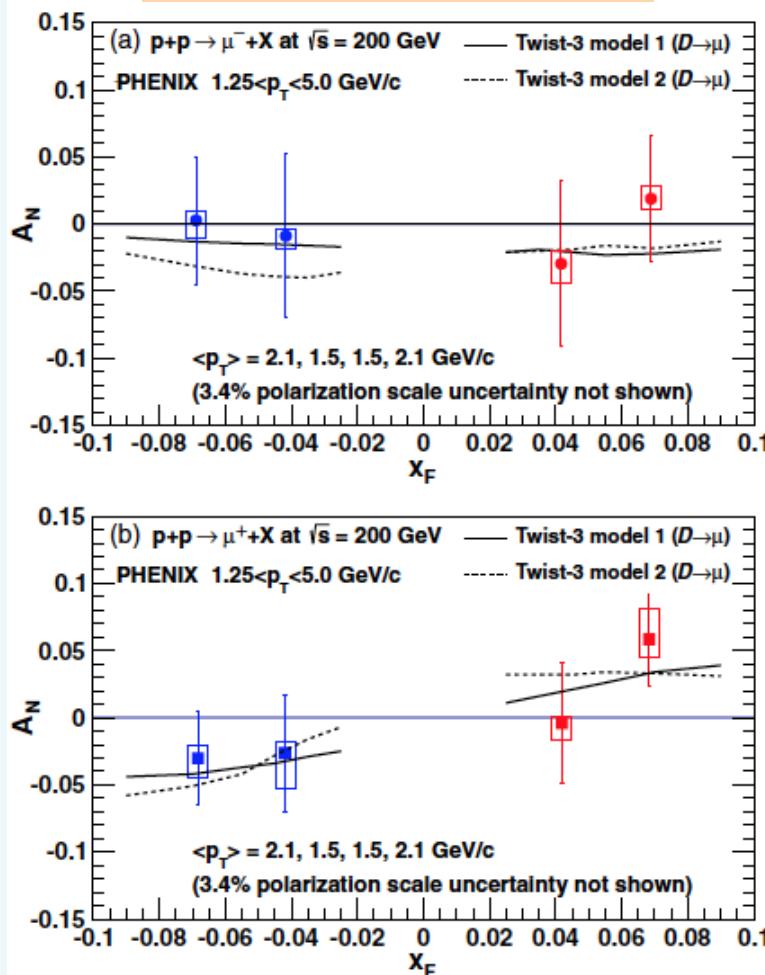
Sensitive to gluons

Used to constrain gluon Sivers effect:
Anselmino et al, PRD 74 (2006), 094011
D'Alesio et al, JHEP 1509 (2015), 119

Open Heavy Flavor A_N



$pp \rightarrow \mu X$
PRD95, 112001 (2017)



Dominated by gluon-gluon fusion

Used to constrain tri-gluon correlation in the Twist-3 collinear framework

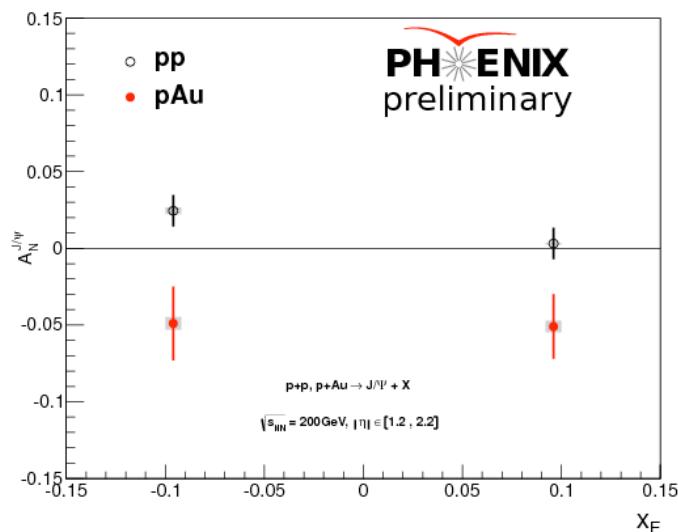
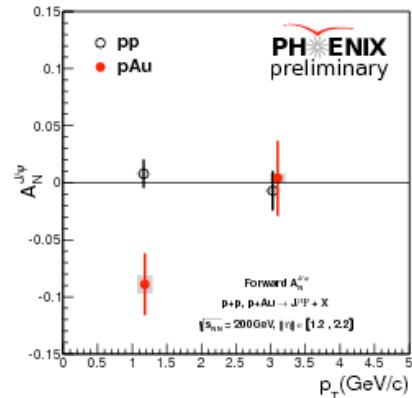
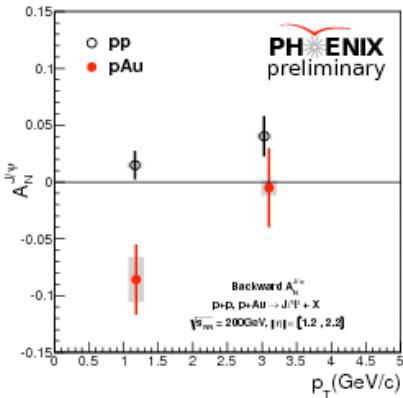
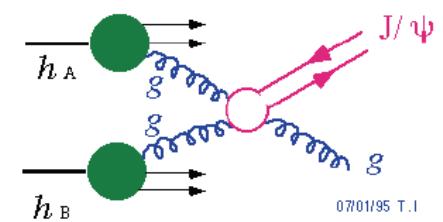
Z.Kang, J.Qiu, W.Vogelsang, F.Yuan,
PRD78,114013

Y.Koike, S.Yoshida, PRD84,014026

Significant reduction in uncertainties expected from 2015 data



$J/\psi A_N$



Improved pp results from 2015!

First ever pA \rightarrow J/ ψ A_N data!

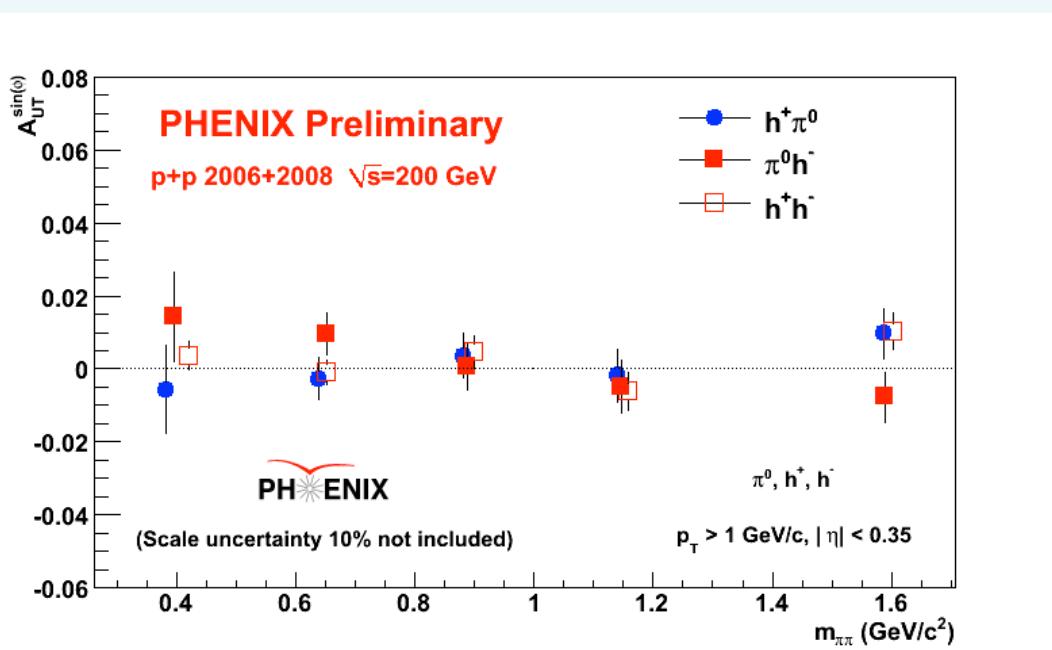
A_N sensitive to J/ ψ production mechanism

F.Yuan, PRD78, 014024:

For non-zero gluon Sivers, A_N vanishes in color octet model, but survives in color singlet model

Access to transversity: IFF

In collinear (Twist-3) framework

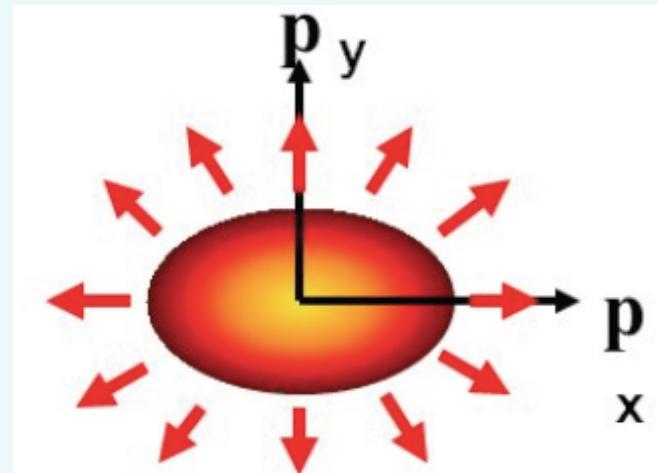
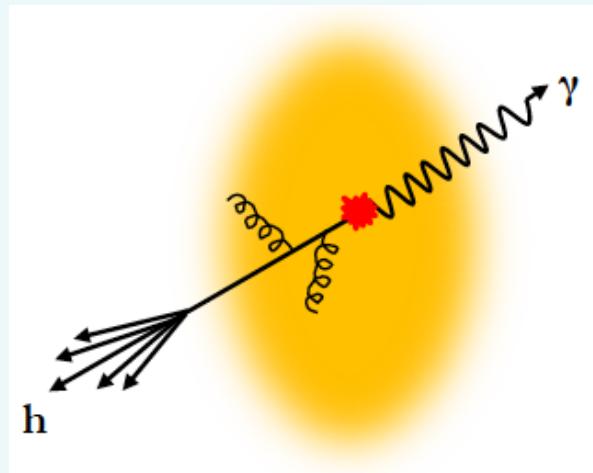


Much more data available
from 2012 and 2015:

$|\eta| < 0.35$: h^+h^- , $h^+\pi^0$, $h^+\pi^0$,
 $\pi^+\pi^-$, $\pi^+\pi^0$, $\pi^+\pi^0$

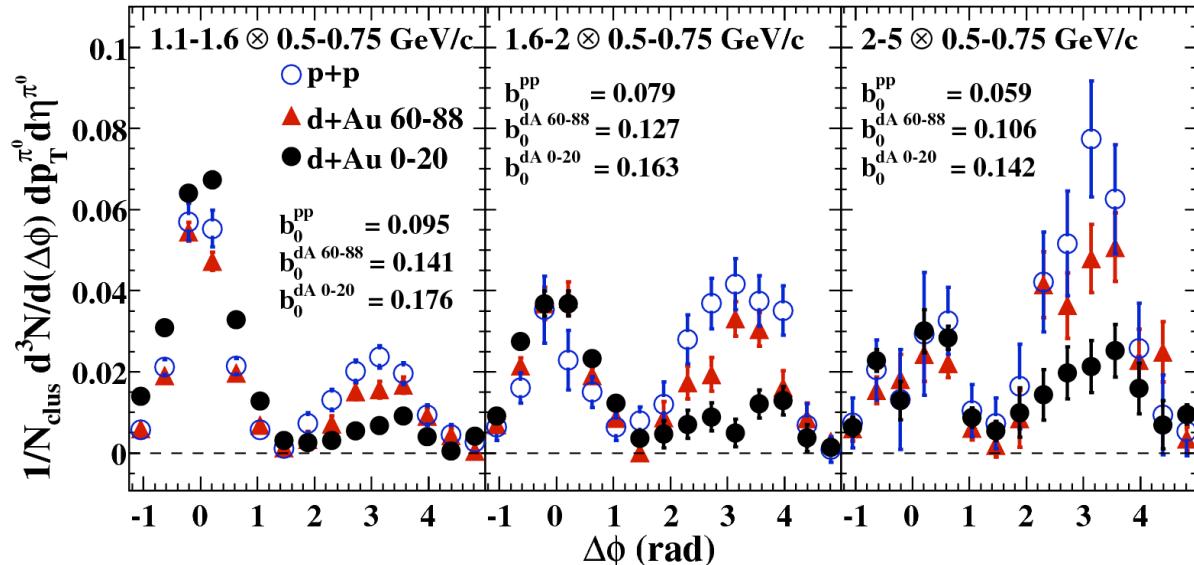
$1.2 < |\eta| < 2.4$: h^+h^-

Correlations, Collectivity



h-h correlation

PRL 107, 172301 (2011)



CGC \Rightarrow suppression of back to back correlation

$$J_{dA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{\sigma_{dA}^{\text{pair}} / \sigma_{dA}}{\sigma_{pp}^{\text{pair}} / \sigma_{pp}}$$

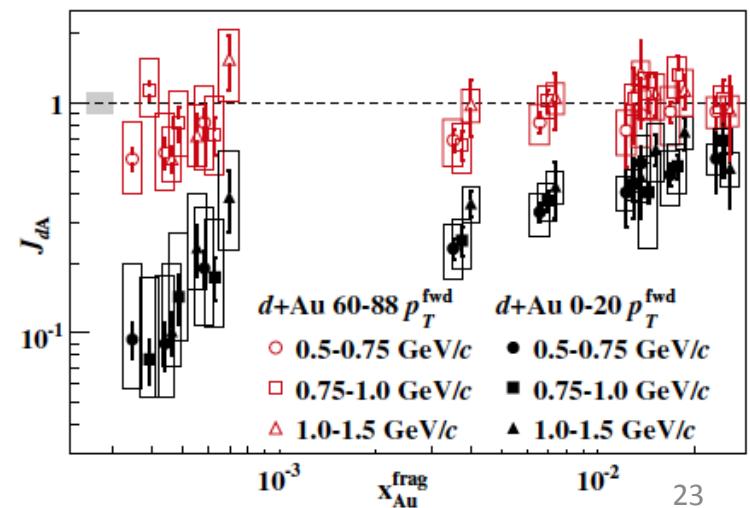
Other mechanisms (including final state effects) may lead to the similar suppression

E.g. CNM energy loss

γ -h correlation: final state effect reduced

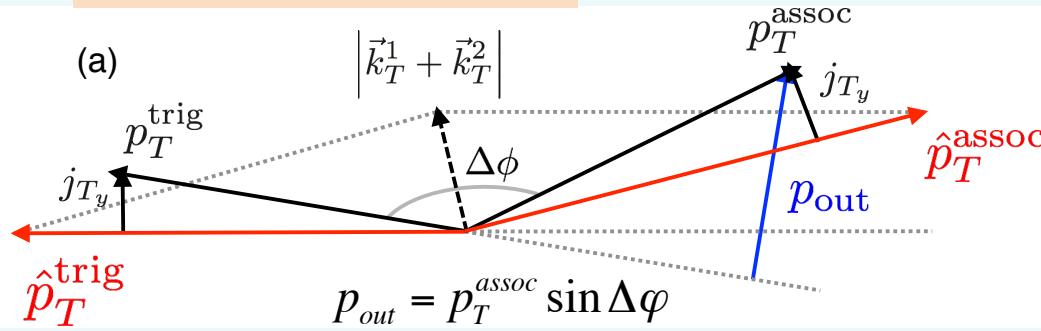
MPC-EX allows for π^0/γ separation to >80 GeV/c

Run16 dA analysis ongoing



π^0 -h $^\pm$ and γ -h $^\pm$ correlation

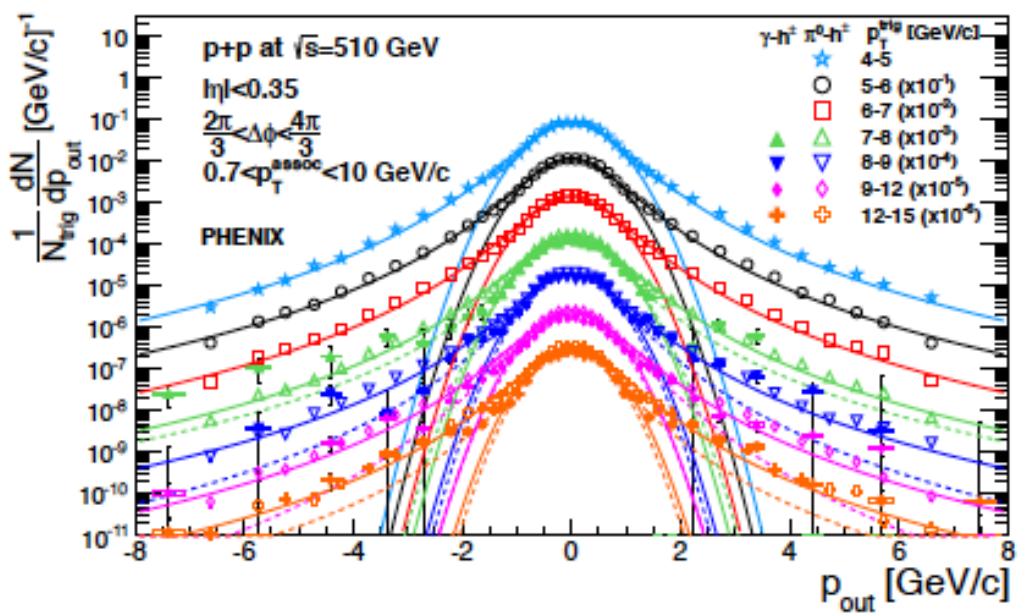
PRD 95, 072002 (2017)



Gives access to non-perturbative transverse momentum effects:

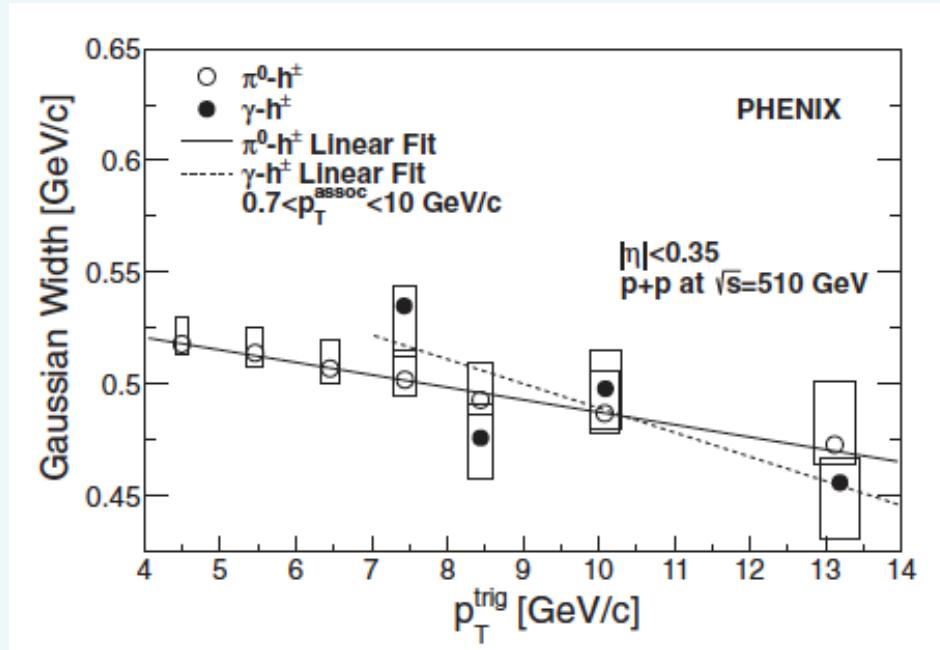
p_{out} includes k_T and j_T

Measure p_{out} from azimuthal correlation, as a function of p_T^{trig}



From TMD factorization, expect increasing transverse momentum (p_{out}) with increasing hard scale (p_T^{trig})

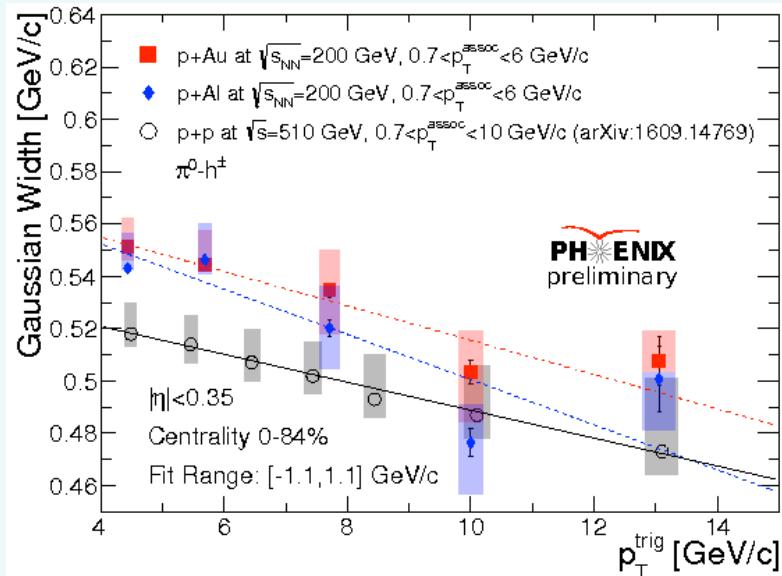
π^0 -h $^\pm$ and γ -h $^\pm$ correlation



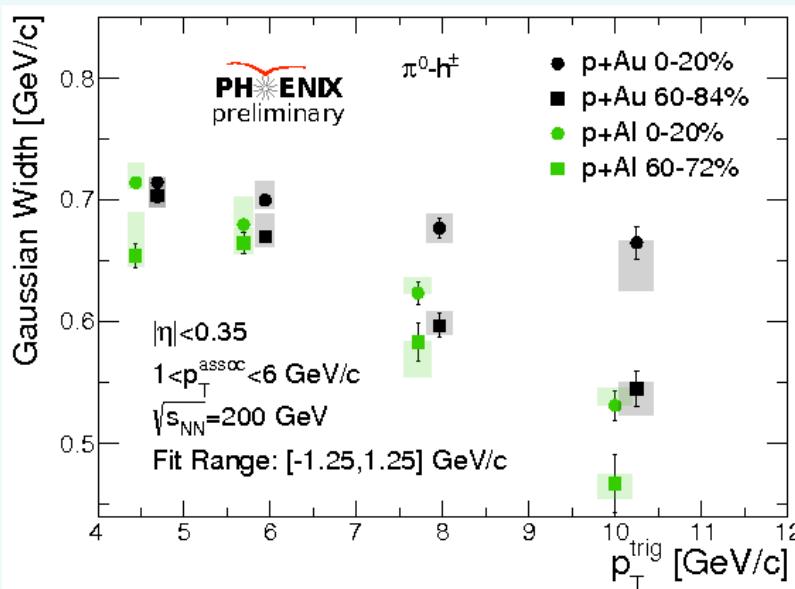
Decreasing width!
Factorization breaking?



π^0 - h^\pm correlation



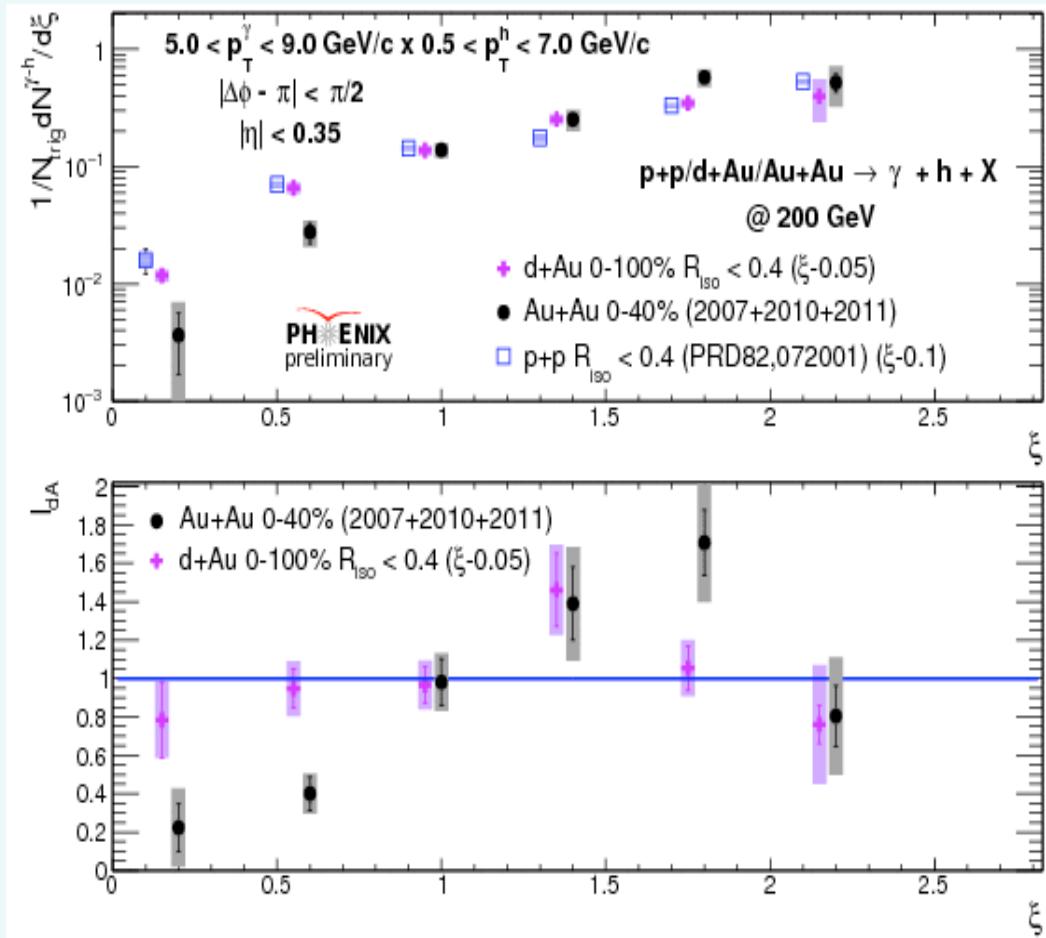
Stronger p_T^{trig} dependence in pA
Stronger gluonic field?
Multiple scattering?



Clear centrality dependence,
particularly in heavy nucleus (Au)
kT broadening?
Multiple scattering?
Flow?



γ -h $^\pm$ correlation => FF



Access FF with integrated away side yield

$$p_T^\gamma \approx p_T^{\text{jet}} \quad z_T = \frac{p_T^h}{p_T^\gamma}$$

$$\varsigma = \ln\left(\frac{1}{z_T}\right) \quad D(\varsigma) = \frac{1}{N_{\text{evt}}} \frac{dN(\varsigma)}{d\varsigma}$$

FF modification:

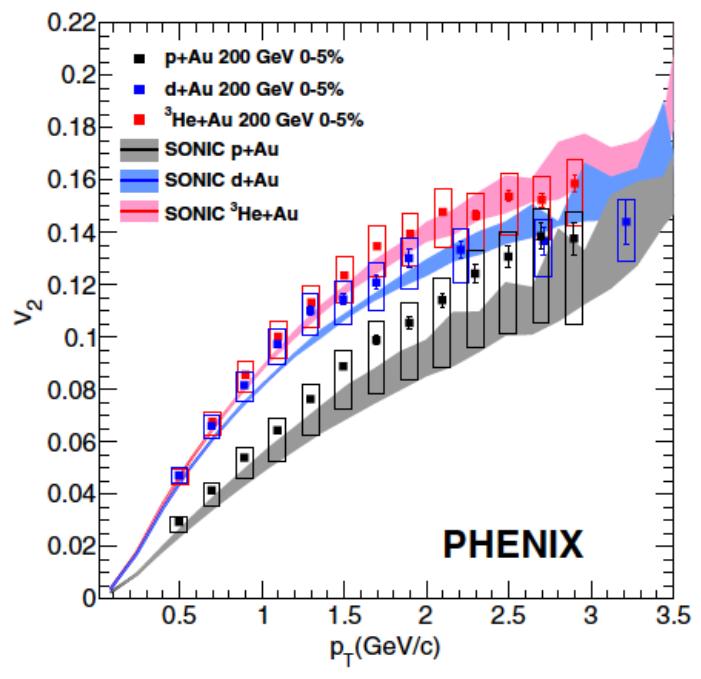
$$I_{dA} = \frac{Y_{dA}}{Y_{pp}} \approx \frac{D_{dA}(\varsigma)}{D_{pp}(\varsigma)}$$

No FF modification in dAu (within uncertainty)

Significant FF modification in AuAu

Collectivity (Flow)

PRD 95, 034910 (2017)



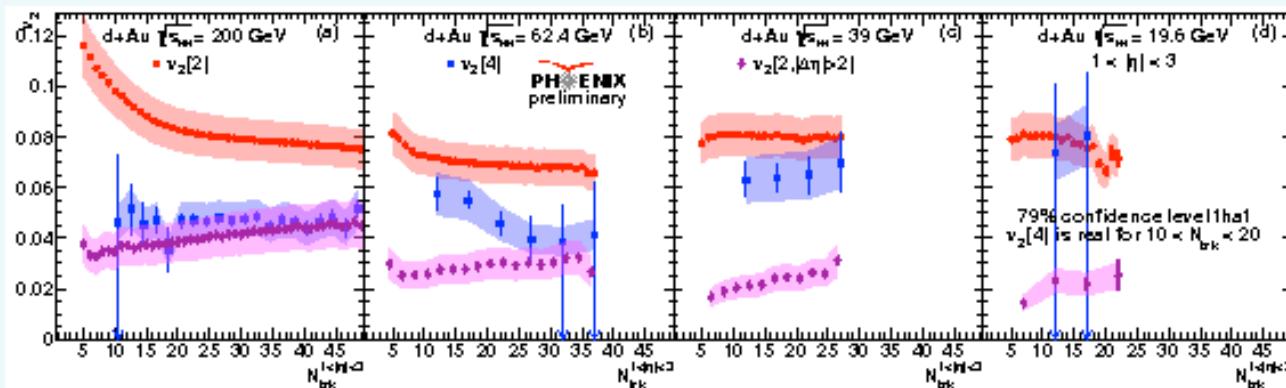
May be contributed by multiple particle correlation in CGC

Geometry and energy scan from PHENIX:

v_n in $p/d/^3\text{He} + \text{Au}$ and $p+\text{Al}$ at $\sqrt{s}=200$ GeV

v_n in $d+\text{Au}$ $\sqrt{s}=200, 62.4, 39, 19.6$ GeV

PID-ed v_n



Summary

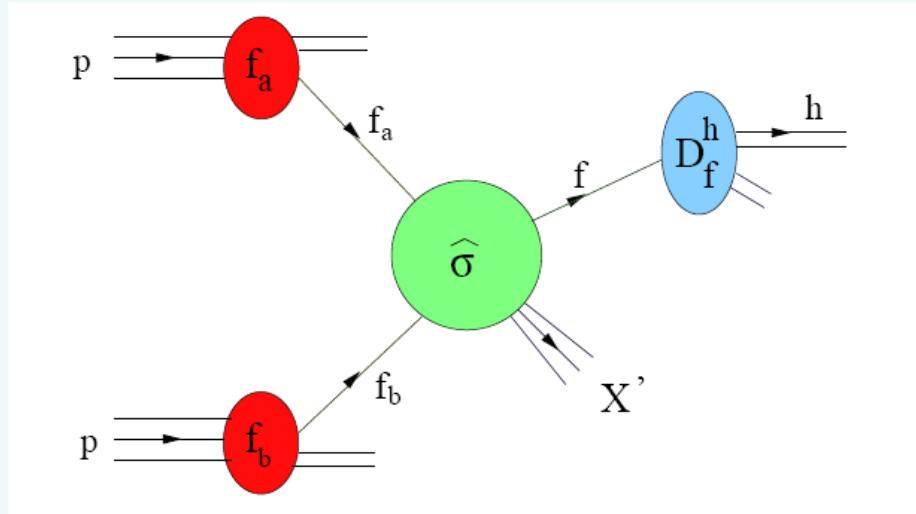
- ✓ A lot of PHENIX results contributing to all aspects of Cold QCD studies
- ✓ A lot more results to come
 - Collected data on disk/tape are being actively analyzed
 - New young researchers joining the collaboration
- ✓ Stay tuned for new PHENIX results!

PHENIX → sPHENIX transition for 2020+ physics: see Nils's talk next

\sqrt{s} [GeV]	p+p	p+Al	p+Au	d+Au	$^3\text{He}+\text{Au}$	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130									
62.4	✓				✓	✓	✓	✓	✓
39					✓			✓	✓
27								✓	✓
20					✓	✓		✓	✓
14.5								✓	✓
7.7								✓	✓

Backup

Factorization – a Cornerstone of QCD



Predictive power (for hard probes):

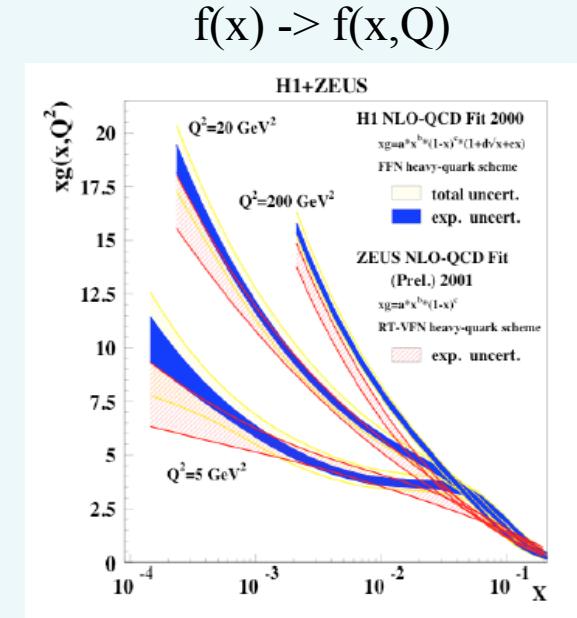
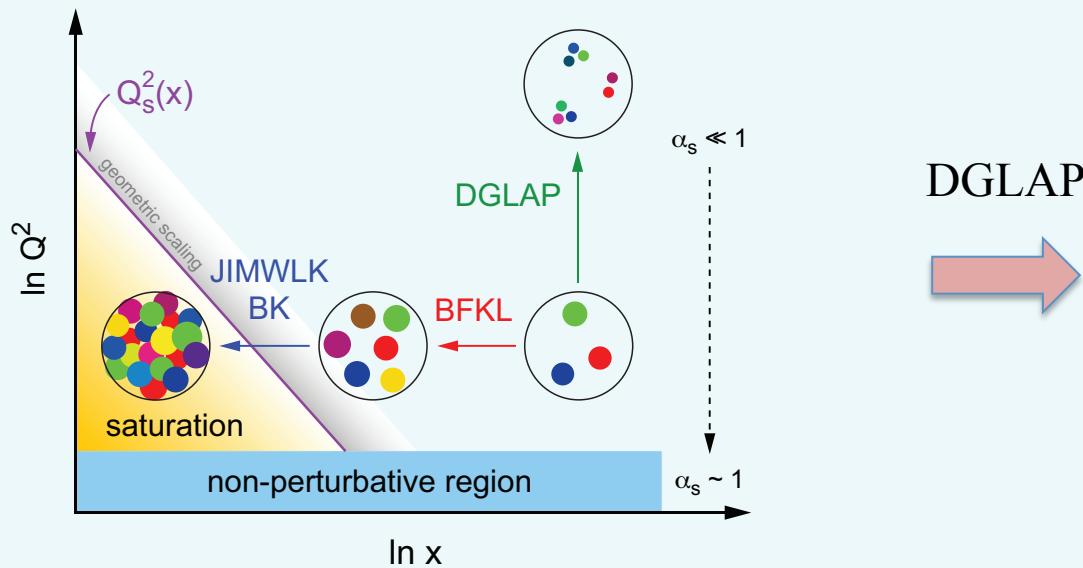
$$\sigma(pp \rightarrow hX) \sim \textcircled{f_a(x_1)} \otimes \textcircled{f_b(x_2)} \otimes \textcircled{\hat{\sigma}^{f_a f_b \rightarrow f}(\hat{s})} \otimes \textcircled{D_f^h(z)}$$

Parton Distribution Func.
from experiment
Universal

Partonic x-section
from pQCD
Process dependent

Fragmentation Func.
from experiment
Universal

Evolution in QCD



Evolution is different (more complicated) for:

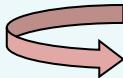
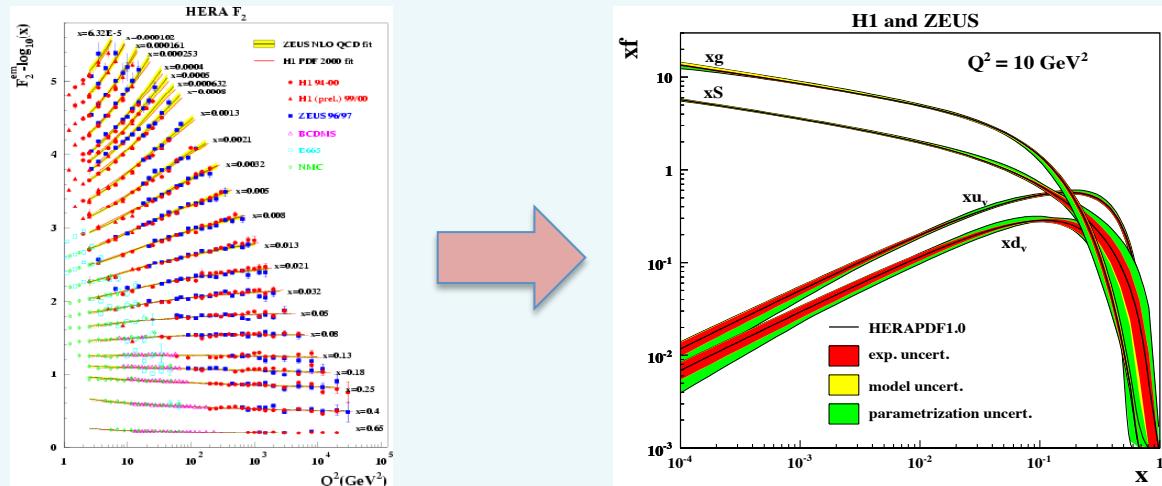
$$\text{TMD: } f(x) \rightarrow f(x, k_T)$$

$$\text{Twist-3: } f(x) \rightarrow T(x, x)$$

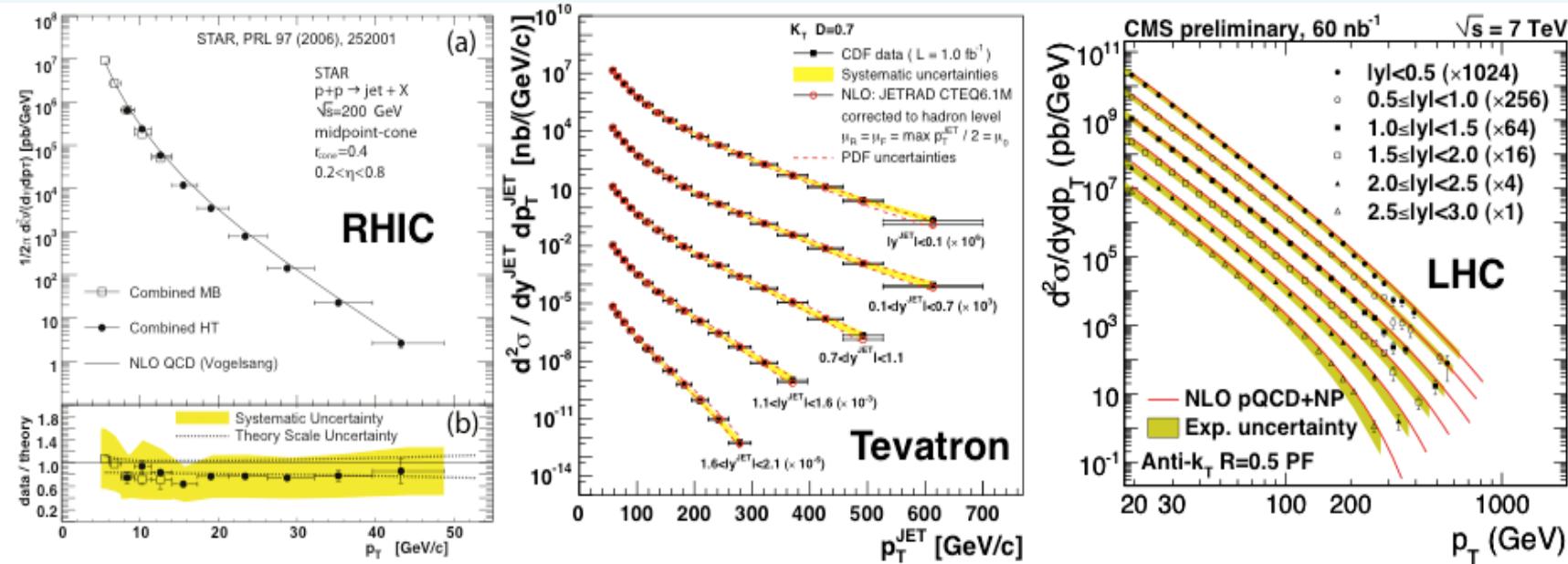
→ Important for Spin effects studies

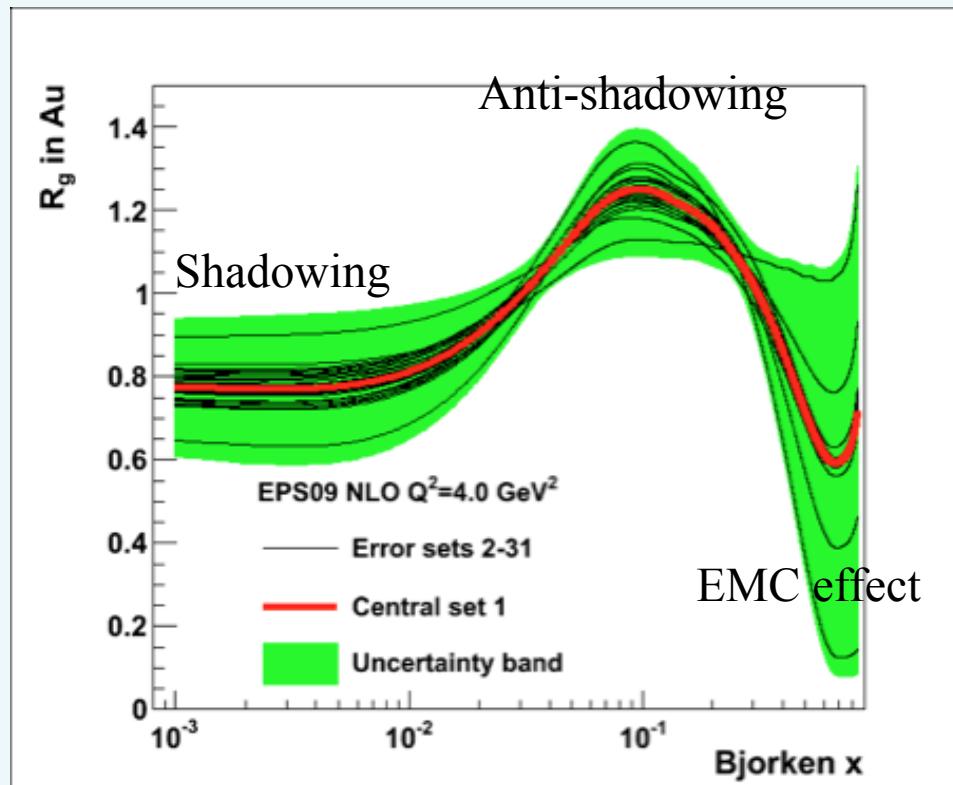
PDF (and FF) Universality

Measure PDFs in ep
at 0.3 TeV (HERA):



Predict p-p and p-pbar at 0.2, 1.96, and 7 TeV



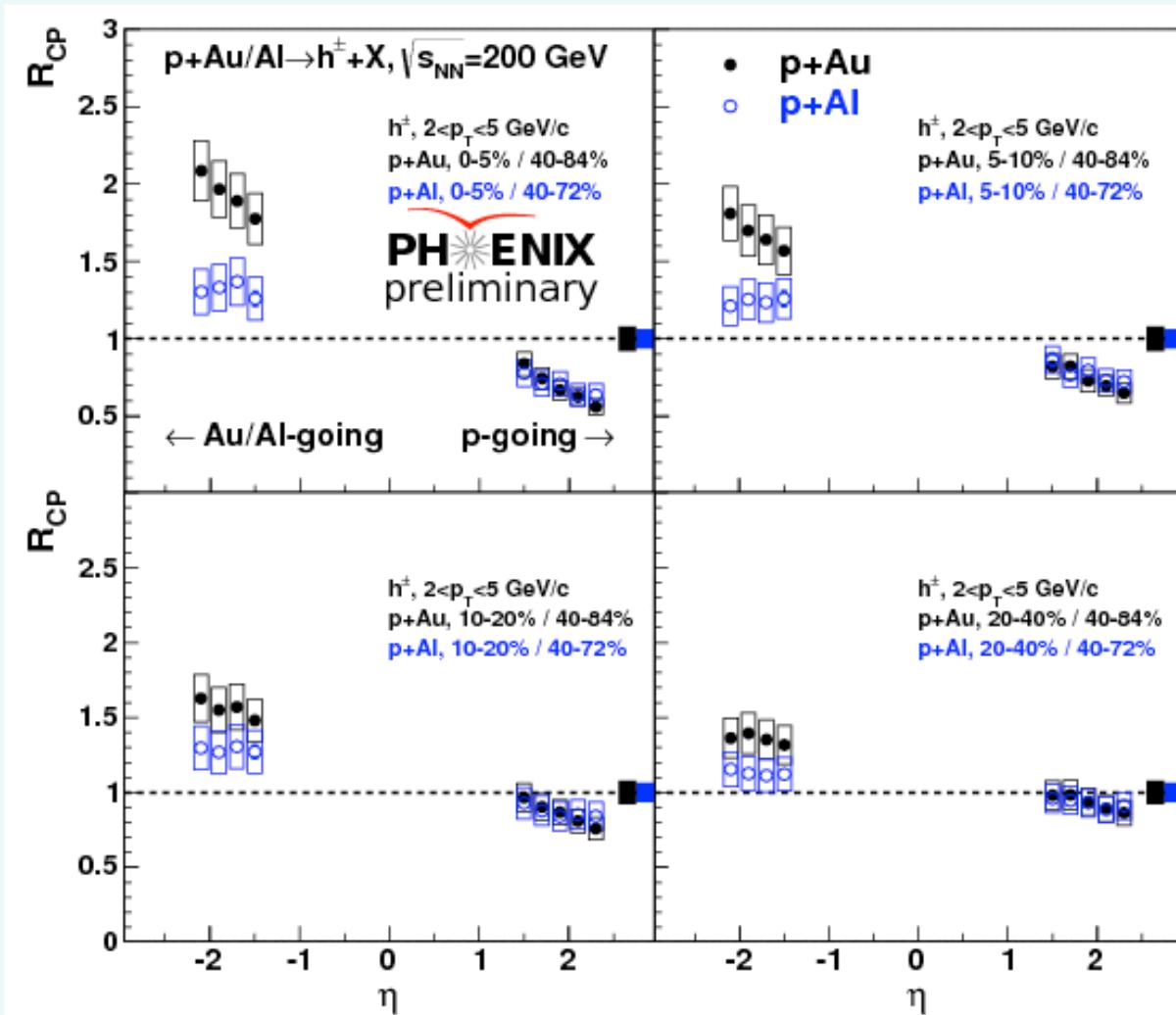


PDF in nuclei are modified compared to nucleon

Also:
 Scattering with nuclear matter
 (initial and/or final effect)
 kT broadening
 Energy loss

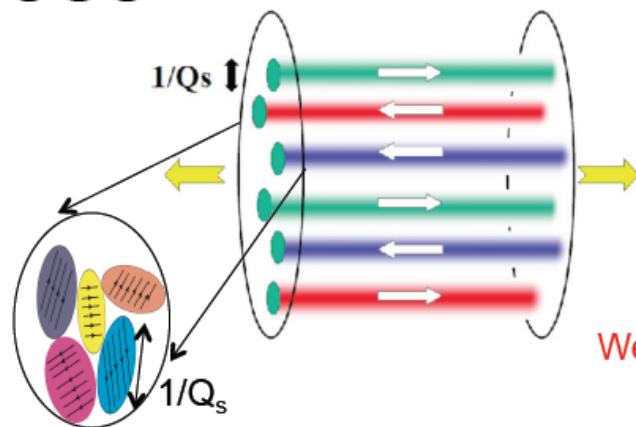
R_{pA} : forward-backward

Nucleus size and rapidity dependence



Examples of initial vs final state scenarios

CGC



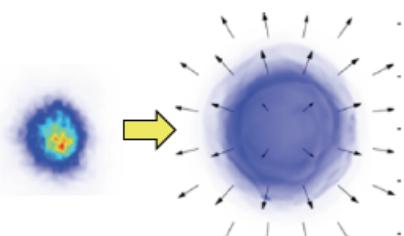
Domain of color fields of size $1/Q_s$, each produce multi-particles correlated across full η .

Uncorr. between domains, strong fluct. in Q_s

More domains, smaller v_n , more Q_s fluct, stronger v_n

Well motivated model framework, need systematic treatment

Hydro



Hot spots (domains) in transverse plane e.g IP-plasma, boost-invariant geometry shape

Expansion and interaction of hot spots generate collectivity

v_n depends on distribution of hot spots (ε_n) and transport properties.

Ongoing debate whether hydro is applicable in small systems